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OF THE

# BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

## No. 139

# SOME TESTS OF LIGHT ALUMINUM CASTING ALLOYS—THE EFFECT OF HEAT TREATMENT

BY

P. D. MERICA, Physicist
and
C. P. KARR, Associate Physicist
*Bureau of Standards*

ISSUED OCTOBER 24, 1919

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By P. D. Merica and C. P. Karr

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## I. INTRODUCTION

During the past 18 months a number of experimental heats of different compositions of light aluminum casting alloys have been poured at the Bureau of Standards foundry, and mechanical and corrosion tests made of the test-bar castings. These tests have not been of a particularly systematic nature, but have been directed at different times toward different objectives, such as (1) the development of a suitable ductile casting alloy, (2) the determination of the resistance of standard alloys to alternating stresses, (3) the effect of heat treatment on the mechanical properties of casting alloys, and (4) the study of the effect of type of test bar. Much of the work was done in connection with the activities of the subcommittee on aluminum of committee B–2 of the American Society for Testing Materials on nonferrous metals and alloys. The grouping of the results of these tests and discussion of them within the scope of one paper is somewhat arbitrary, but constitutes perhaps the best presentation of some of the facts which have developed during the course of the investigations.

Many of the questions studied have received attention at the hands of previous investigators; a summary of all of this work, together with a bibliography of it, is contained in a recent publication.[1]

## II. PREPARATION OF THE ALLOYS

The alloys were all prepared with commercially pure materials: 99 per cent aluminum; Commercially pure copper; Thermit manganese; Commercially pure nickel; Commercially pure spelter; magnesium, 99.9 per cent pure. Hardeners, prepared in a crucible, were used for the introduction of these elements, as follows: (*a*) 50 per cent copper, 50 per cent aluminum; (*b*) 50 per cent aluminum, 25 per cent copper, 25 per cent manganese; (*c*) 80 per cent aluminum, 20 per cent nickel. In preparing a heat, the required amount of hardener together with the aluminum was placed in the crucible and melted; a No. 40 plumbago crucible was generally used. The metal was stirred with a graphite rod, the pot removed from the furnace, and the magnesium added and submerged within the melt with tongs. Rock salt was added as a flux during the melting, and just before pouring an ounce or so of zinc chloride was thrown on the metal to bring up and remove the dross.

The earlier heats, viz, H1, H2, E5, E6, E7, A2, A4, E8, E–C and D, G1, G2, C15, C16, C17, C18, C19, A30, and Z31, were melted in an oil-fired furnace, the others in a gas-fired one. The highest temperature during melting and the pouring temperature were measured with a thermocouple protected with iron pipe.

All specimens, except those of type *II*, were poured in green sand, skin dried with the torch; those of type *II* were poured in core sand.

Heats X–1 and 2, XE–3 and 4, C56, XE–5 and 6, XE–7 and 8, XE–9 and 10, C20, C57, C49, C59, C53, E21, E22, H5, H6, Z14, E9, G7, G8, Z15, Z16, G9 and G10 were melted in a covered crucible, the others without cover.

## III. METHODS OF TEST

All test bars for the tensile test were machined to 0.505 inch diameter over the gauge length of 2.25 inches. Types *I*, *II*, *III*, and *VII* (see pages 6 and 7 and Figs. 1 and 2) were tested with

[1]Aluminum and its Light Alloys, Circular No. 76 of the Bureau of Standards, 1919; also in Chem. and Met. Engineering, 1919.

wedge grips. Type *IV* had threaded ends, types *V* and *VI* had shoulders with which the specimens were held in self-centering grips.

The yield point and proportional limit were determined with the Riehle improved extensometer; the yield point was taken as that value of the stress at which the slope of the stress-strain curve was twice that of the elastic portion of it.

The Brinell hardness, using a ball of 10 mm diameter, a load of 500 kg applied for 30 seconds, and the sceleroscope hardness with magnifying hammer were determined on sections taken from the heads of the specimens.

Table 1 contains a summary of the results of the tests of all specimens as well as of the chemical compositions, and pouring and melting temperatures, the data of heat treatment, and other information.

## IV. INFLUENCE OF FORM OF TEST SPECIMEN

In Figs. 1 and 2 are shown sketches of the forms of test bars used in these experiments. The form *I* is often used for metals of high shrinkage, such as steel or manganese bronze. The test piece is taken from one of the lower legs and may be machined to any desired form; in these tests the form *IIA* was used, the test specimens being tested with wedge grips. The form *II* has been accepted as standard by the American Society for Testing Materials in its specification B–10–18 for 88:10:2 bronze; the dimensions of the bar used in these experiments do not correspond exactly to those of this specification, however. The bar may be machined for use with wedge grips or with threaded holders; in these experiments all bars cast into this form were tested with wedge grips. Forms *III* and *VII* are ordinary types of test bars from which a standard test specimen of 0.505 inch diameter may be obtained to be tested with wedge grips. The *No. IV* is given in the tables to a bar cast to the same dimensions as *No. III*, but machined with threaded ends. Bars *V* and *VI* are of the shoulder type, and are machined to 0.505 inch diameter. Bars *III*, *IV*, *V*, *VI*, and *VII* were cast in pairs, horizontally, in green sand, with gate and riser for each pair.

The test results show that *No. I* gives very low values of the tensile strength, owing to the large section of the cast piece. This type is not satisfactory for aluminum alloys. In all of the tests

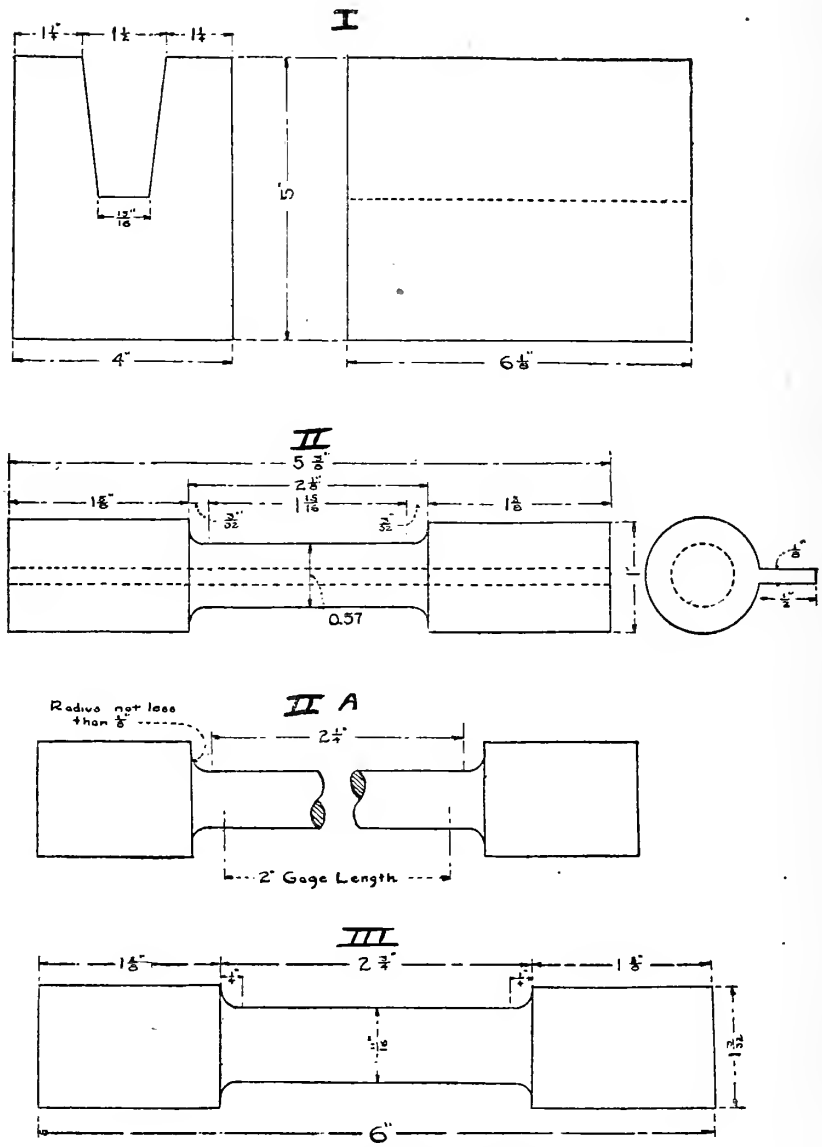


FIG. 1.—*Forms of test bars used*

*I*, a type often used for metals of high shrinkage such as for steel or manganese bronze.

*II*, the type recommended by the American Society for Testing Materials for 88 : 10 : 2 bronze; in the tests described herein the cast bars were machined to the form IIA and tested with wedge grips.

*III*, a common type of test bar, poured horizontally in green sand, with gate and riser; the specimen is machined to the form IIA and tested with wedge grips.

*IV;* this number is given in the tables to the same cast bar as *III* but machined with threaded ends and tested in a self-centering holder.

in which a direct comparison was made between bars of types *II* and *III* the bars of type *III* gave higher values both of the tensile strength and of the elongation than those of type *II*. (See heats E7, Table 1*b;* G1 and G2, Table 1*c;* H1 and H2, Table 1*d*.)

The tensile strength obtained from bars of type *III* was always less than that from bars of types *V*, *VI*, and *VII* on the same alloy. (See heats E9, Table 1*b;* E23, E24, and E27, Table 1*e*.) This is

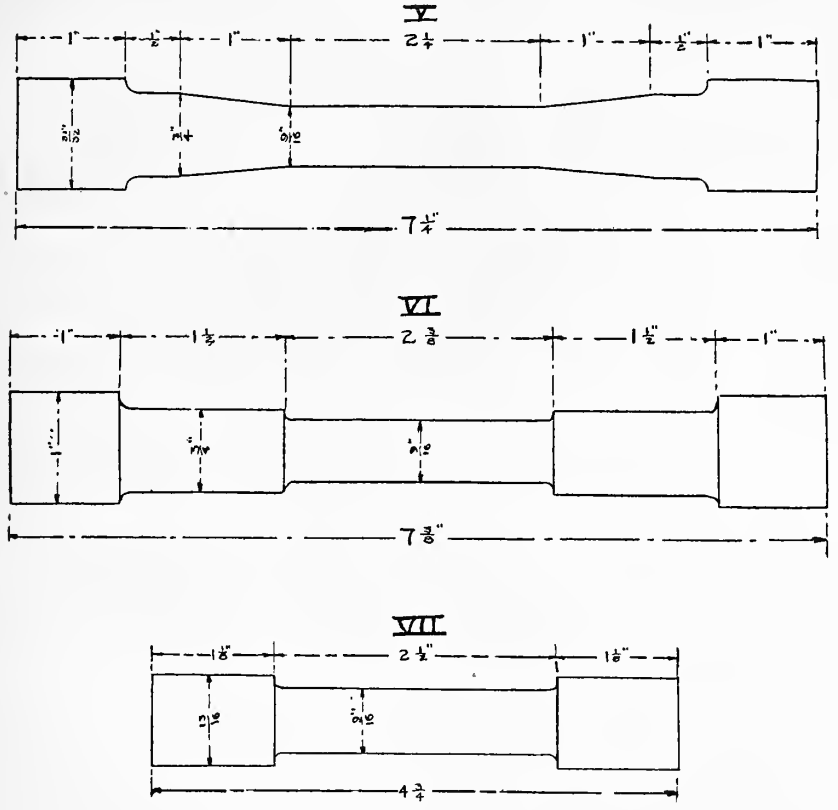


FIG. 2.—*Form of test bars used*

*V;* shoulder type of test bar; it is machined to 0.505 inch diameter over 2¼ inches.
*VI;* shoulder type of test bar; it is machined to 0.505 inch over 2¼ inches.
*VII;* small bar similar to *III;* it is machined to 0.505 inch diameter and tested with wedge grips.
All of these bars are cast horizontal in green sand with gate and riser.

undoubtedly due to the difference of section of the cast specimen; the bar *III* is cast with a diameter of 11/16 inch over the gage length, whereas the others are cast with one of 9/16 inch. The fact that such a small difference of section of the cast bar makes such an appreciable difference in the tensile strength shows the necessity for precise statement of this section in describing test bars

in specifications for light alloys. The diameter of 9/16 inch, used for many of these test bars, would seem to be a most satisfactory one, as it provides amply, but with a minimum amount of machining, for obtaining the 0.505 inch diameter specimen from it.

It was expected that direct comparison between the types *III* and *VII*, tested with wedge grips, and *V* and *VI*, gripped at the shoulder and self centering, would indicate the advantage of the latter type. It is generally conceded that wedge grips should not be used for aluminum alloys which are brittle if the best and most uniform results are to be obtained. Indeed, many instances of variation of tensile properties of test bars of type *III* from the same heat were ascribed to the fact that they were not properly centered in the testing machine. The results of tests of bars of heat E9, Table 1*b*, show that, in this case at least, the bars tested with wedge grips (*VII*) gave as good results as those of the shoulder type (*V* and *VI*). It is to be observed that the effect of the use of wedge grips is much influenced by the carefulness of the operator and the accuracy of alignment of the testing machine; the possibility of obtaining low results is always existent when they are used.

## V. INFLUENCE OF MELTING AND POURING TEMPERATURES

The influence of pouring temperature on the mechanical properties of light alloys has been the subject of much study. (See footnotes 1 and 2.) As the pouring temperature is increased the tensile strength of the alloy decreases, due largely to its larger grain size. This is illustrated in the results of the tests of heat G1–C–P, Table 1*c*, and of E27, Table 1*e*.

The effect of the maximum temperature of melting as distinct from that of pouring has been given apparently much less attention. Two tests were made to ascertain the effect of maximum temperature of melting, using the same pouring temperature. The pot of metal was melted, allowed to cool to 700° C, and test bars cast at this temperature. The pot was then replaced in the furnace and heated to a higher temperature, removed from the furnace, and bars cast at this higher temperature; the pot was then allowed to cool again to 700° C and the remainder of the metal poured into bars at this temperature. Heats G1, Table 1*c*, and E27, Table 1*e*, were poured in this manner. The difference between the bars

[2] H. W. Gillett, The Influence of Pouring Temperature on Aluminum Alloys, Eighth International Congress of Applied Chemistry, Sec. II, 2, p. 105; 1912.

heated during melting to 850° and those to 790° C in the case of G1, both being poured at 700° C, was not noticeable. In the case, however, of heat E27 a falling off in tensile strength is noticeable after heating at the higher temperature, 950° C.

The two tests, while too few to be conclusive, seem to confirm the current belief that the maximum temperature during melting must not be allowed to go too high, probably not over 850° C.

## VI. INFLUENCE OF CHEMICAL COMPOSITION

The subject of the effect of chemical composition on the mechanical properties of light aluminum alloy castings has been much investigated. (See footnotes 1, 3, and 4.)

The metals which are principally used to impart hardness and strength to aluminum are copper, zinc, and magnesium. Each of these is soluble to a limited extent in aluminum, and it is to the increased hardness of these several solid solutions that the value of these additions is due. The present tests have been largely of alloys with copper as the principal hardening component. In this country the use of an alloy containing approximately 8 per cent of copper is very general; in fact the majority of sand castings at least are made of this composition. It is an excellent alloy for general purposes, hard and readily machined. Its only disadvantage is its brittleness; test bars will average only about 2 per cent elongation in 2 inches. Castings made of it will resist wear well, and will not break under stresses which are below the yield point; they will not, however, withstand appreciable deformation without fracturing. It would seem that for many purposes an alloy might be desired which would be tougher and less fragile, so that instead of fracturing under accidental overload, it would yield slightly without failure.

A number of different compositions were tested with the purpose of ascertaining what tensile properties could be obtained with an alloy having appreciable ductility. In choosing the compositions for the alloys tested, the maximum solubility of copper in aluminum was used as a guide; this is approximately 4 per cent. Beyond this amount the excess copper is present in the form of a brittle constituent which can not markedly increase the hardness but does decrease the ductility.

[3] H. C. H. Carpenter and C. H. Edwards, Alloys of Aluminum and Copper, Eighth Report to Alloys Research Committee, Proc. Inst. Mech. Eng.; 1907.

[4] W. Rosenhaim and L. S. Archbutt, Alloys of Aluminum and Zinc, Tenth Report to the Alloys Research Committee, Proc. Inst. Mech. Eng.; 1912.

The test results of alloys G, Table 1*c*, of alloys H, Table 1*d*, and with E23, E24, E26, and E27, Table 1*e*, indicate the range of tensile properties which may be expected in a ductile alloy. It appears that there should be no difficulty in obtaining with a number of compositions the following tensile properties:

| | | |
|---|---|---|
| Tensile strength | lbs. per sq. in. | 20 000–25 000 |
| Elongation in 2 inches | per cent | 5 |

It is to be observed that such alloys will not be as hard as the well-known one containing 8 per cent copper, and they will have a slightly higher shrinkage; low shrinkage and high hardness must be sacrificed in order to obtain the higher ductility.

One of the most striking facts apparent from a consideration of the mechanical tests of different compositions of light alloys is the hardening and embrittling effect of small additions of magnesium to alloys containing copper. This is evident from a comparison of heats C15, C16, C17, and E27, all of which contain from 3 to 3.5 per cent of copper, the first three containing in addition from 0.4 to 1.3 per cent magnesium. With this copper content the elongation is lowered from about 8 to 2.5 per cent by the addition of magnesium, with only a slight increase in tensile strength. This fact is well illustrated also in heats G7 and 8 and H 5 and 6. In each of these cases the metal was melted and bars poured without magnesium; thereupon the magnesium was added to the pot and additional bars poured. The tensile strength of each composition was increased by 10 to 20 per cent, the elongation was decreased by 60 to 80 per cent by the addition of the magnesium. It seems apparent that high ductility can not be obtained in cast alloys containing magnesium.

The results of the tests of heats E23, E24, E26, and E27, Table 1*e*, containing only copper, and of heats G, Table 1*c*, and H, Table 1*d*, containing nickel and manganese in addition to copper, would indicate that tensile strengths as high as 25 000 pounds per square inch can not be obtained with the use of copper alone, but that nickel or manganese must also be added. On the other hand, if a tensile strength of 18 000 pounds per square inch is sufficient, it appears somewhat questionable whether better results are not obtained with copper alone; the addition of manganese seems to produce more uniform test results, but the resulting alloys are somewhat less ductile than those with copper alone.

Two heats of commercial aluminum were cast into test bars without the addition of hardener of any sort. The test results are given in Table 1*a*.

At one time there were two lots of notch-bar ingots in the foundry which seemed to show a marked difference in brittleness as tested quite roughly by bending the ingot. Inasmuch as the question of "brittle ingots" was a quite live one at the time, a heat of test bars of each lot was poured under the same conditions in order to ascertain whether the brittleness as so indicated would persist in the cast test bars. It will be noticed that there is a marked difference in the ductility of the bars of the two heats; the bars of the lot A–4 averaged only about 15 per cent elongation as compared with 29 per cent for lot A–2. It was, however, lot A–2 of which several ingots had been found to be brittle.[5] It is interesting to note the difference in silicon content of the two heats; the one with the high silicon content gave the low values of ductility.

## VII. EFFECT OF HEAT TREATMENT

It is well known that alloys containing copper with or without magnesium, in the forged or rolled condition may be improved by heat treatment consisting of quenching from about 500° C and allowing to age for several days. (See footnotes 1, 6, and 7.) A number of tests were carried out to determine to what extent the mechanical properties of cast alloys might be improved by a similar treatment. Since it would not be desirable in many cases actually to quench castings in water, owing to the possibility of their cracking, the heat treatment which was applied in all of these tests consisted of heating at 500° C for two hours followed by cooling in air; the specimens were then allowed to age several days before testing. Such a heat treatment could readily be applied to most commercial castings of aluminum alloy. In the tables the specimens which were so treated are marked "ac" or "fc" in column 10, depending on whether they were cooled in air or in the furnace after annealing.

Test specimens of about 30 heats were so treated. In all but five or six cases there was found to be an increase in tensile strength resulting from this treatment amounting to from 5 to 50 per cent of the strength of the cast, unheat-treated bars. In those cases in which the heat treatment resulted in a decrease of strength the whole group of bars of the heat was of inferior quality, cast and heat-treated ones alike.

---

[5] It must be observed that not all ingots of the lot A–2 were brittle, and that there was no assurance that all of the ingots were actually originally of the same melt except that they belonged to the same purchase lot.

[6] Wilm, Metallurgie, 8, p. 650; 1911.

[7] Cohn, Elektrotechnik u. Maschinengau, 31, p. 430; 1913.

The effect of heat treatment on the elongation was more erratic; in the majority of cases the average elongation of the heat-treated bars was lower than that of the unheat-treated ones, but in several cases there resulted an increase in ductility. Thus in the case of heats G7, Table 1*c*, and H5, Table 1*d*, the elongation of the treated bars was approximately 20 per cent less than that of the unheat-treated ones, while in the case of heat E27, Table 1*e*, the elongation of the treated bars was approximately 50 per cent greater.

The presence of magnesium seems in general to increase the amount of the hardening produced by heat treatment, at least in the amounts used in these tests. This is illustrated in the results of the tests of heats G7 and 8, Table 1*c*, and of H5 and 6, Table 1*d*. This is quite in accord with the fact that the presence of magnesium in duralumin increases the amount of hardening produced by heat treatment.[8]

It was observed that during the annealing of the specimens at 500° C those which contained magnesium became covered with a dark gray coating of oxide, whereas those containing no magnesium remained quite bright and unaltered superficially during this treatment.

It would seem that the application to light aluminum castings of heat treatment of a type similar to that described above has commercial possibilities, inasmuch as it is possible in this manner to obtain high values of tensile strength and hardness in alloys containing only from 3 to 4 per cent of hardener, which have a considerable ductility.

## VIII. RELATION BETWEEN TENSILE PROPERTIES AND HARDNESS

The structure of cast aluminum alloys is discussed below, and it is shown that these alloys fracture in most cases at the grain boundaries, the strength depending thus on the cohesion at these boundaries. The hardness of the alloys depends principally, however, on the hardness or cohesion of the grains themselves. It is therefore not surprising that the tensile strength and the hardness of cast light alloys do not bear any simple relation to each other.

Thus the alloys of Table 1*b*, containing about 8 per cent of copper, have an average Brinell hardness of about 65, a scleroscope hardness of about 20, together with an average tensile strength

[8] Merica, Waltenberg and Scott, The Heat Treatment and Constitution of Duralumin, Sci. Paper No. 337 of the Bureau of Standards; 1919. Also in Bulletin Amer. Inst. Mech. Eng., No. 151, p. 1031; 1919.

of about 19 000 pounds per square inch. The alloys of the G1 and G2 series, Table 1*c*, have about the same average tensile strength, but their Brinell hardness is only about 50, scleroscope hardness about 11. Again the tensile strength of the bars of heat H5, Table 1*d*, is greater than the average tensile strength of the 8 per cent copper alloy, but their hardness is less.

The effect of heat treatment is to increase both the tensile strength and the hardness, although not always in the same proportion. Thus, in Table 1*e*, the tensile strength and hardness of the specimens of C56 were increased in about equal proportions, the tensile strength of the bars of C20 was increased in greater proportion than the hardness, while in the case of C44 the effect of heat treatment was to decrease the tensile strength and to increase the hardness.

## IX. MICROSTRUCTURES

Photomicrographs illustrating typical microstructures of aluminum light alloys are shown in Figs. 3 to 16; all of the alloys of which the structures are shown contain copper as the principal hardening element. Elsewhere [9] it has been shown that at 525° C approximately 4 per cent of copper is dissolved in solid solution in aluminum as $CuAl_2$; the solubility of this compound in aluminum diminishes at lower temperatures, and is about 1 per cent at 300° C. Cast alloys containing copper therefore have a structure consisting of grains of aluminum solid solution of cored or dendritic arrangement, surrounded partially or completely by envelopes of the excess $CuAl_2$. This is illustrated in the figures.

The elements nickel and manganese also form compounds with aluminum which are only slightly soluble in aluminum and form envelopes in the same manner as does $CuAl_2$. The greater the sum of the percentages of copper, nickel, and manganese the greater the volume of the compounds formed and the more complete and continuous the grain envelopes. Compare, for example, the structure of E7–M11, Fig. 6, containing 8 per cent of copper with that of G1–I, Fig. 7, containing 2 per cent of copper plus 1 per cent of manganese.

The path of fracture in cast alloys having this structure whenever possible follows these envelopes which are hard and brittle. This is shown in Figs. 14, 15, and 16, photomicrographs taken

[9] Merica, Waltenberg, and Freeman, The Metallography of Aluminum and Its Light Alloys with Copper and with Magnesium, Sci. Paper No. 337 of the Bureau of Standards; 1919. Also in Bulletin Amer. Inst. Mech. Eng. No. 151, p. 1031; 1919.

near or at the fractured ends of tensile-test specimens. When the envelopes are not complete and continuous, the fracture is forced in places to cross the grains. In Fig. 16 it is noted that the fracture occurs both at the envelopes and across the grains.

Besides increasing the volume of the envelopes of $CuAl_2$, the increase of copper content causes an increase in the average concentration of the solid solution $CuAl_2$ in aluminum; the hardness of the alloy depends principally on the hardness of the grains, which is increased roughly in proportion to the concentration of the solid solution. Increases of copper content therefore increases the hardness of the cast alloy, and up to a certain amount, about 3 per cent, also increases the tensile strength. Beyond that amount, although the hardness continues to increase, the increase in volume of the envelopes produces a more favorable path of rupture under tensile stress, and the tensile strength is not further increased.

The ductility of the alloys depends on the relation between the tensile strength and the stress necessary to produce permanent deformation. If the former appreciably exceeds the latter the alloy will exhibit ductility, otherwise it will not. Within a structure such as that shown in Fig. 6, consisting of grains completely surrounded by the brittle envelopes, fracture at the envelopes occurs before the stress can be increased sufficiently to produce deformation. In a structure such as that of Figs. 9 and 10, the envelopes are broken up and discontinuous; the path of fracture is forced at least partially across the grains, and deformation within the grains can be produced before fracture occurs. The alloy of Fig. 6 exhibits practically no ductility; those of Figs. 9 and 10 from 4 to 6 per cent elongation.

## X. RESISTANCE TO CORROSION IN THE SALT-SPRAY TEST

The resistance of these alloys to corrosion was determined by use of the salt-spray test. This test consists of exposing the samples to a continuous fog of salt water, produced by atomizing a 20 per cent solution of salt (sodium chloride) in water.[10] Although this test is not considered as entirely satisfactory, it is thought that the results produced represent with a fair degree of accuracy the results obtained in actual service, especially under marine conditions.

[10] A. N. Finn, Method of Making Salt-Spray Test. Proceedings Am. Soc. Test Mats., XVIII, Part I, p. 237; 1918.

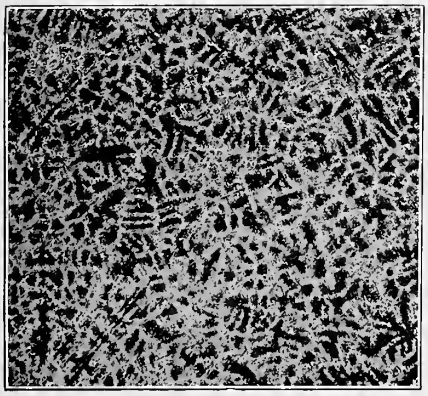

FIG. 3.—*Specimen E5–M4.* ×20

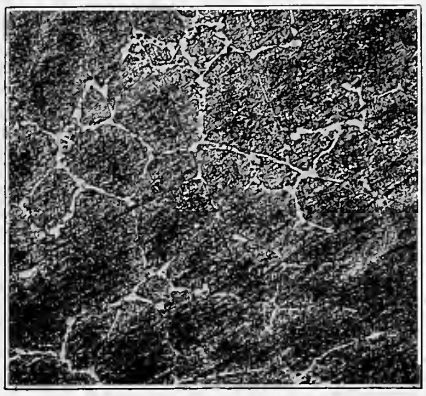

FIG. 4.—*Specimen E5–M4.* ×100

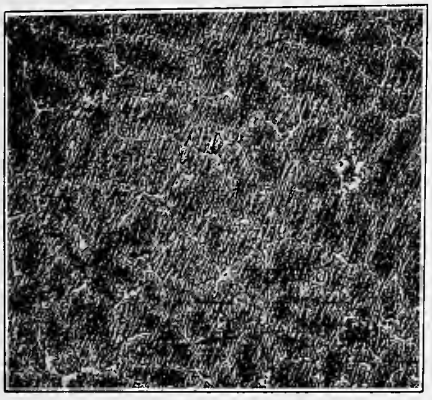

FIG. 5.—*Specimen E6–M7.* ×50

FIG. 6.—*Specimen E7–M11.* ×50

The structure of the alloy containing 8 per cent of copper. All specimens etched with 0.1 per cent NaOH

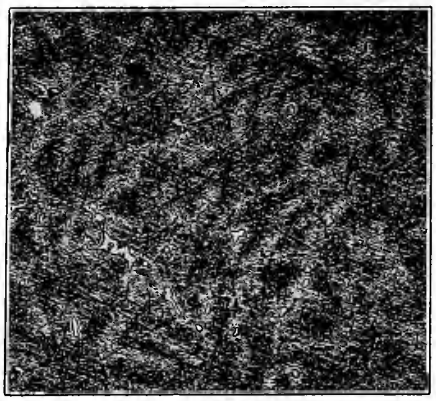

FIG. 7.—*Specimen G1–I.* ×50

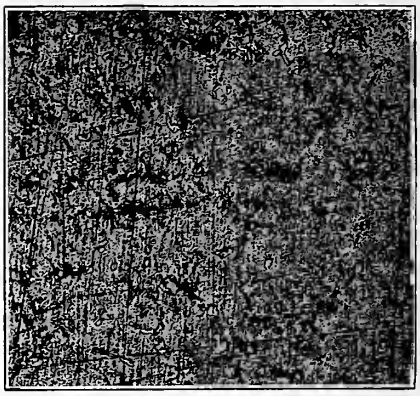

FIG. 8.—*Specimen G1–D.* ×50

FIG. 9.—*Specimen H1–2.* ×50

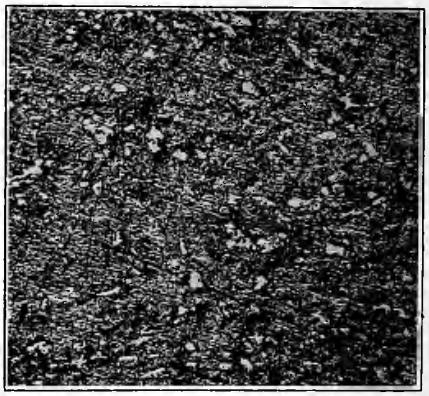

FIG. 10.—*Specimen A2–1.* ×50

Structure of cast alloys. All specimens etched with 0.1 per cent NaOH

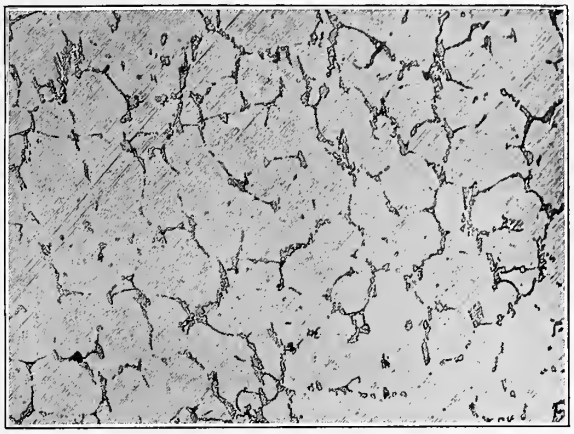

FIG. 11.—*Specimen H6–C.* ×100

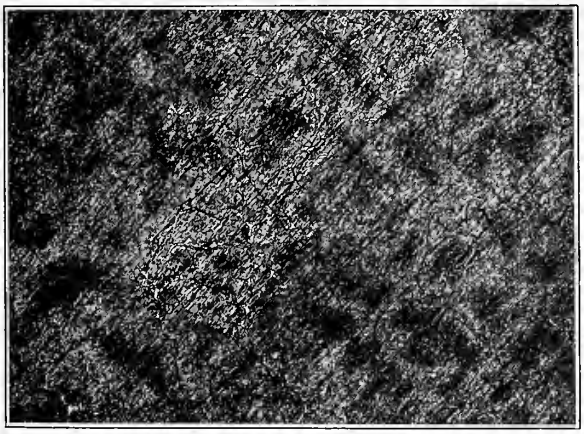

FIG. 12.—*Specimen C15–B.* ×50

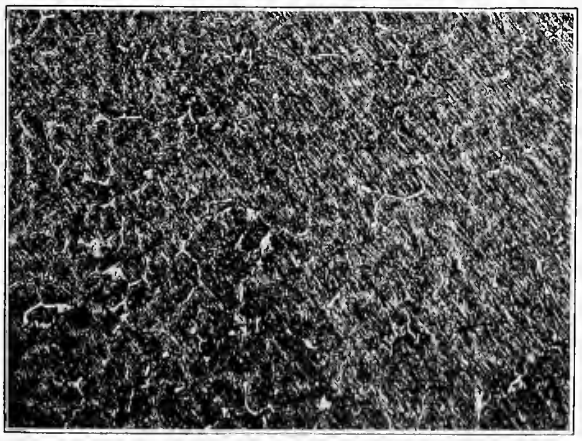

FIG. 13.—*Specimen C19–C.* ×50

FIG. 14.—*Specimen 97 E.* ×150

FIG. 15.—*Specimen E5–M1.* ×50

The path of fracture in cast alloys

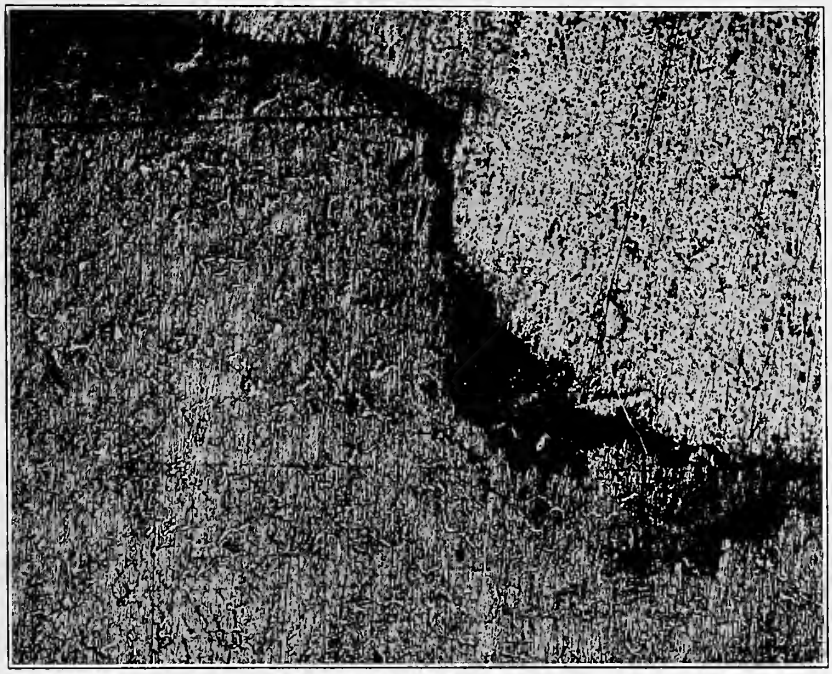

FIG. 16.—*Specimen H2-4.* ×50

The path of fracture in cast alloys

The alloys were subjected to the salt-spray test for two periods of one month each, and were examined at the end of each period to determine the relative amount of corrosion. This was estimated by appearance only, as it is practically impossible to determine it by loss in weight on account of the adherence of the products of corrosion and the lack of a satisfactory reagent to remove the rust without affecting the metallic aluminum.

The alloys were cast 1/4 inch thick, about 1/8 inch was then milled from one surface so that one exposed surface was as cast, and the other was machined. The specimens were 2 inches wide and 4 inches long.

The designation of the cast alloys, with their composition and treatment, is given in the following table:

| Marked | Treatment | Composition |
|---|---|---|
| A-30-A | As cast | Al+5 per cent Mg. |
| A-30-A-A | Annealed 500° C | Do. |
| CA 40 A | As cast | Al+3 per cent Cu+1 per cent Mg. |
| CA 40 A A | Annealed 500° C | Do. |
| G 1 F | As cast | Al+2 per cent Cu+1 per cent Mn. |
| G 1 F A | Annealed 500° C | Do. |
| Z 31 A | As cast | Al+13½ per cent Zn+3 per cent Cu. |
| Z 31 A A | Annealed 500° C | Do. |
| E A | As cast | Al+8 per cent Cu. |
| E A A | Annealed 500° C | Do. |

These cast alloys appeared very slightly and about equally corroded after two months exposure to the salt spray, although the alloy containing 5 per cent Mg (A-30-A, and A-30 A-A) appeared somewhat better than the others. No difference could be detected between the milled surface and the surface as cast, or between the specimen as cast and annealed.

The authors are indebted to A. N. Finn for his assistance in carrying out the salt-spray tests.

## XI. RESISTANCE TO THE ACTION OF ALTERNATING STRESSES

Light aluminum casting alloys are called upon not only to resist the action of a constant load or stress but also frequently to resist vibratory stresses, as for example, in a crank case. There is little published information on the subject of the resistance of light alloys to the action of alternating stresses. Elmendorf [11] finds that cast commercial aluminum, subjected to the

[11] A. Elmendorf. Tables and Charts Resulting from the Testing of Cast Aluminum on a White-Souther Rotary Testing Machine, Amer. Mach., 41, p. 811; 1914.

White-Souther test will withstand 1 000 000 reversals of stress at a maximum fiber stress of 10 000 pounds per square inch. Jeffries [1] states that the cast alloy containing 8 per cent of copper will withstand an unlimited number of alternations of tensile stress between 0 and 12 000 pounds per square inch.

Three compositions of alloy were tested in this respect: (1) That containing 8 per cent of copper (the E series); (2) That containing from 2 to 3 per cent copper and from 12 to 15 per cent zinc (the Z series); and (3) that containing from 1.5 to 2 per cent copper and from 1.5 to 2 per cent manganese (the G series). The test bars were cast horizontal in green sand, with gate and riser, each being 27 inches long and 7/8 inch in diameter. The bars were machined for test to a uniform diameter of 0.740 inch.

A modification of the old Wöhler or White-Souther machine was used for the testing. Each bar was supported at the two outside points and the load applied at the two intermediate third points by means of weights in the usual manner. These points were 8 inches apart. The specimens were then rotated at an approximately uniform rate of 1000 rpm, the number of rotations to rupture being indicated in the usual manner with a revolution counter.

The results of the tests are given in Table 8 and in the curves of Fig. 17. For comparison the tensile properties determined on the usual type of tensile test bar, of the heats from which alternating stress test bars were poured and tested, may be seen in Tables 1*b*, 1*c*, and 1*f*.

There seems to be no marked difference between the different compositions as regards their resistance to alternating stresses. The series E seems to be somewhat superior to the others, the series G, slightly inferior. The curves in Fig. 17 are drawn through the mean of the mean number of alternations to rupture for each stress. The following values are taken from the three curves:

| | Series *E* | Series *Z* | Series *G* |
|---|---|---|---|
| Maximum fiber stress withstood at 1 000 000 alternations | 11 000 | 10 400 | 9500 |
| Maximum fiber stress withstood at 10 000 000 alternations | 8200 | 7200 | 6900 |
| Maximum fiber stress withstood at 100 000 000 alternations | 6000 | 5000 | 5000 |

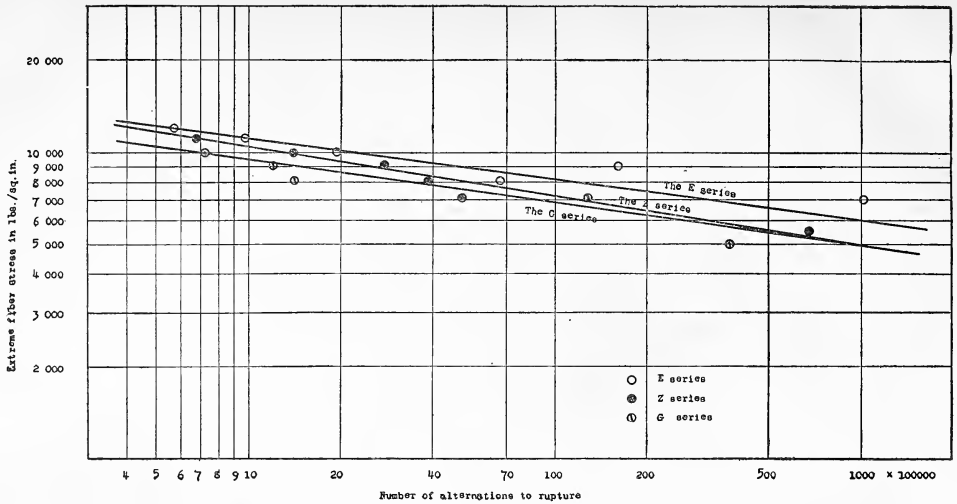


FIG. 17.—*The resistance of cast aluminum alloys to the action of alternating stresses*

○=*E* series, containing 8 per cent copper; ◉=*Z* series, containing 12 to 15 per cent zinc, 2 to 3 per cent copper; ϕ=*G* series, containing 1.5 to 2 per cent copper, 1.5 to 2 per cent manganese. The resistance of cast alloys to alternating stresses. The maximum fiber stresses and number of alternations to rupture are plotted on logarithmic paper; the resulting curves are of the form

$$S = \frac{K}{N^c}$$

when $S$=extreme fiber stress

$N$=number of alternations to rupture.

These results are apparently best expressed in the form of curves or in such a table, but the following equations of the usual type are calculated from the mean curves:

For the $E$ series $S = 68\ 000\ N^{-0.132}$
For the $Z$ series $S = 93\ 000\ N^{-0.159}$
For the $G$ series $S = 65\ 000\ N^{-0.139}$
When $S$ = the maximum fiber stress in pounds per square inch.
$N$ = number of alternations to rupture.

These equations may be compared with that given (loc. cit.) by Elmendorf:

$$S = 48\ 000\ N^{-0.113}$$

for cast commercial aluminum. It appears that the resistance to the action of alternating stresses does not increase in proportion as the tensile strength or the hardness of the alloy increases. Thus according to Elmendorf aluminum alone will withstand as many alternations of stress at fiber stresses of from 7000 to 10 000 pounds per square inch as will the alloy *G*, which has a tensile strength from 20 to 50 per cent higher than that of the aluminum.

The authors are indebted to L. J. Larson for his assistance in carrying out the above tests.

## XII. SUMMARY AND CONCLUSIONS

The tensile properties and the hardness of a number of different compositions of light aluminum casting alloys have been determined; the resistance to corrosion compared and the resistance to the action of alternating or vibratory stresses determined of a few commonly used compositions.

It is advisable to use for tensile tests a test bar cast almost to size; a bar cast with the test length 9/16 inch in diameter, afterwards machined to 0.505 inch gives satisfactory results. The use of a type of test specimen which can be gripped in a self-centering holder in the testing machine is recommended.

A study of the effect of chemical composition on the mechanical properties has shown that it is possible to obtain an alloy containing from 2 to 3 per cent of copper together with 1 or 2 per cent of nickel, manganese, or both, which will have a reasonable amount of ductility, and it is believed that an alloy of this type should have commercial value. Tensile properties suggested for such an alloy are the following:

| | |
|---|---|
| Tensile strength ..... pounds per square inch .. | 20 000–25 000 |
| Elongation in 2 inches, not less than ..... per cent .. | 5 |

The addition of magnesium to alloys containing copper reduces in a marked manner the ductility, but increases the tensile strength and the hardness.

The effect of heat treatment on test-bar castings, consisting of annealing at 500° C, cooling in air from this temperature and allowing to age for several days, is to increase the tensile strength and the hardness; the ductility of the alloy is generally decreased, but may in some cases be increased. The presence of magnesium in the alloy in amounts of from 0.5 to 1.5 per cent seems to increase the hardening effect of heat treatment. The heat treatment of light aluminum castings would seem to have commercial possibilities.

The microstructure of the different alloys was studied and it was found that fracture in them prefers a path along the brittle envelopes surrounding the grains of aluminum, consisting of the various eutectics which are formed with the added metals or their compounds with aluminum.

Two months' exposure in the salt spray produced only slight corrosion of several compositions of cast alloys. There was no very appreciable difference between the different compositions in resistance to corrosion.

A study of the resistance to the action of alternating stresses of three compositions of light cast alloys (*E* series, containing 8 per cent copper; *Z* series, containing 2 to 3 per cent copper, and 12 to 15 per cent zinc; *G* series, containing 1.5 to 2 per cent copper, and 1.5 to 2 per cent manganese) showed that there was no marked difference in the behavior of the three alloys in this test, although the *E* series was somewhat superior and the *G* series somewhat inferior to the others. All of the three alloys will withstand 10 000 000 complete reversals (tension to compression) at a maximum fiber stress of 7000 pounds per square inch.

The authors are indebted to Miss H. C. Baker and Col. A. C. Krynitzky for carrying out most of the mechanical tests.

## TABLE 1.—Mechanical Properties

### (*a*) CAST COMMERCIAL ALUMINUM

| Heat and No. | Chemical composition | | | | | Temperature | | Form of test bar | Heat treatment | Tensile properties | | | | | | Hardness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Copper | Magnesium | Manganese | Nickel | Other metals | Maximum temperature during pouring | Pouring temperature | | | Ultimate strength | Yield point [a] | Proportional limit | Elongation in 2 inches | Reduction of area | Fracture | Scleroscope mag. hammer | Brinell, 500 kg |
| | P. ct. | P. ct. | P. ct. | P. ct. | Per cent | °C | °C | | | Lbs./in.² | Lbs./in². | Lbs./in.² | Per cent | Per cent | | | |
| A2-A | ..... | ..... | ..... | ..... | 0.5 Fe | ..... | 700 | III | ac [b] | 13 700 | 2300 | ..... | 25.5 | 22.4 | ..... | 4–5 | 25 |
| D | ..... | ..... | ..... | ..... | .2 Si | ..... | 700 | III | ac | 13 600 | 2600 | ..... | 28.0 | 30.2 | ..... | 4–5 | 27 |
| B | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 13 700 | 2600 | ..... | 29.0 | 37.3 | ..... | 4–5 | 26 |
| C | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 14 000 | 2400 | ..... | 29.0 | 34.4 | ..... | 4–5 | 26 |
| A4-A | ..... | ..... | ..... | ..... | .5 Fe | ..... | 700 | III | ac | 12 600 | 2000 | ..... | ..... | ..... | ..... | 4–5 | 26 |
| B | ..... | ..... | ..... | ..... | .4 Si | ..... | 700 | III | ..... | 12 500 | 2300 | ..... | ..... | ..... | ..... | 4–5 | 25 |
| C | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 13 000 | ..... | ..... | ..... | ..... | ..... | 4–5 | 26 |

### (*b*) CAST ALLOYS CONTAINING APPROXIMATELY 8 PER CENT OF COPPER

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E5-M1 | (8) | ..... | ..... | ..... | 1 Ha [c] | ..... | 700 | I | ..... | 13 600 | ..... | ..... | 2 | ..... | ..... | 20 | 57 |
| 2 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | I | ..... | 13 600 | ..... | ..... | 2 | ..... | ..... | 21 | 67 |
| 3 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 21 | 65 |
| 4 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 18 500 | ..... | ..... | 3 | ..... | ..... | 18 | 65 |
| E6-M5 | 7.2 | ..... | ..... | ..... | 0.4 Fe | ..... | 700 | I | ..... | 8900 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 6 | ..... | ..... | ..... | ..... | .2 Si | ..... | 700 | I | ..... | 10 200 | ..... | ..... | 3 | ..... | ..... | 21<br>23 | 77<br>74 |
| 7 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 17 200 | ..... | ..... | 2 | ..... | ..... | 17 | 61 |
| 8 | ..... | ..... | ..... | ..... | 2 Ha [c] | ..... | 700 | III | ..... | 17 200 | ..... | ..... | 4 | ..... | ..... | 16 | 61 |
| E7-M10 | (8) | ..... | ..... | ..... | ..... | ..... | 700 | I | ..... | 8900 | ..... | ..... | 2 | ..... | ..... | 22 | 80 |
| 11 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | I | ..... | 14 200 | ..... | ..... | 3 | ..... | ..... | 21 | 77 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | | | | | | | 700 | III | | 13 700 | | | 2 | | | 11 | 43 |
| 13 | | | | | | | 700 | III | | 14 200 | | | 3 | | | 13 | 45 |
| E7-1 | (8) | | | | | | 700 | III | | 23 200 | | | 4 | | | | |
| 2 | | | | | | | 700 | III | | 23 400 | | | 4 | 2 | | | |
| 3 | | | | | | | 700 | II | | 22 800 | | | 4 | | | | |
| 4 | | | | | | | 700 | II | | 21 700 | | | 0 | 1.5 | | | |
| E–C | (8) | | | | | | 700 | III | | 19 500 | 3500 | | 3 | 1 | | 17 | 66 |
| D | | | | | | | 700 | III | | 15 700 | 3500 | | 2 | 1 | | 16 | 63 |
| E8-12 | 8.0 | | | | | | 700 | III | | 19 500 | | | 2.5 | 3.6 | | 15 | 57 |
| 13 | | | | | | | 700 | III | | 22 400 | | | 2.5 | 1.2 | | 13 | 67 |
| E9-A | 8.6 | | | | | | (700) | III | | 21 300 | | 8300 | 2 | 1.9 | | | |
| B | | | | | | | (700) | III | | 22 300 | | 11 300 | 1 | 1.9 | | | |
| C | | | | | | | (700) | III | | 21 500 | | 11 800 | 2 | 2.0 | | | |
| D | | | | | | | (700) | III | | 19 600 | | 7500 | 1.3 | 2.0 | | | |
| E | | | | | | | (700) | V | | 19 500 | | | 1.3 | 2.0 | Flaw | | |
| F | | | | | | | (700) | V | | 20 900 | | 9000 | 1.5 | 2.0 | Flaw | | |
| G | | | | | | | (700) | VI | | 24 200 | | 8800 | 1.8 | 2.0 | | | |
| H | | | | | | | (700) | VI | | 22 800 | | 8800 | 1.0 | 2.9 | | | |
| I | | | | | | | (700) | VII | | 19 800 | | 9200 | 1 | 1.6 | Flaw | | |
| J | | | | | | | (700) | VII | | 24 000 | | 7500 | 1 | 2.5 | | | |
| K | | | | | | | (700) | VII | | 24 100 | | 8500 | 2 | 2.5 | | | |
| L | | | | | | | (700) | VII | | 24 100 | | 5500 | 2 | 2.0 | | | |
| E21-E | 7.3 | | | | | 900 | 700 | VI | | 21 900 | | 4000 | 2 | 3 | | | |
| F | | | | | | 900 | 700 | VI | | | | | | | | | |
| E22-H | 8.4 | | | | | 900 | 700 | VI | | 17 400 | | 5800 | 1.3 | 1.5 | | | |
| B | | | | | | 900 | 700 | VI | | 17 200 | | 6300 | 1.0 | 2.0 | | | |
| C | | | | | | 900 | 700 | VI | | 17 700 | | 6000 | 1.3 | 2.5 | | | |
| D | | | | | | 900 | 700 | VI | | 14 000 | | | .5 | 2.5 | | | |
| C48-A | 7.4 | 0.6 | 0.2 | | | 850 | 700 | III | ac | 16 200 | | | 1 | .4 | | 26 | 86 |
| G | | | | | | 850 | 700 | III | ac | 20 100 | | | 2 | 0 | | 25 | 86 |
| B | | | | | | 850 | 700 | III | | 7900 | | | 2.5 | 0 | | 26 | 82 |
| F | | | | | | 850 | 700 | III | | 9900 | | | 2.5 | .4 | | 26 | 86 |

[a] Stress at which slope of the strain curve becomes twice that of the elastic portion.
[b] ac means that the specimen was annealed 2 hours at 500° C and cooled in air.
[c] Ha is a hardener of composition given in footnote *b*, p. 25.

## TABLE 1—Continued

### (c) CAST ALLOYS CONTAINING COPPER AND MANGANESE

| Heat and No. | Chemical composition | | | | | Temperature | | Form of test bar | Heat treatment | Tensile properties | | | | | | Hardness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Copper | Magnesium | Manganese | Nickel | Other metals | Maximum temperature during pouring | Pouring temperature | | | Ultimate strength | Yield point | Proportional limit | Elongation in 2 inches | Reduction of area | Fracture | Sclerescope mag. hammer | Brinell, 500 kg |
| | P. ct. | P. ct. | P. ct. | P. ct. | Per cent | °C | °C | | | Lbs./in.² | Lbs./in.² | Lbs./in.² | Per cent | Per cent | | | |
| G1-M14 | 2.6 | ..... | 0.8 | ..... | 0.5 Fe | ..... | 700 | I | ..... | 14 000 | ..... | ..... | 6 | ..... | ..... | 12 | 45 |
| 15 | ..... | ..... | ..... | ..... | .20 Si | ..... | 700 | I | ..... | 14 000 | ..... | ..... | 4 | ..... | ..... | 12 | 50 |
| 16 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 21 000 | ..... | ..... | 7 | 5.4 | ..... | 11 | 48 |
| 17 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 19 100 | ..... | ..... | 6 | 4.9 | ..... | 11 | 48 |
| G1-1 | (2) | ..... | (1) | ..... | ..... | ..... | 700 | III | ..... | 19 300 | ..... | ..... | 6 | 4.5 | ..... | 14 | 50 |
| 2 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 19 300 | ..... | ..... | 5 | 5 | ..... | 14 | 50 |
| 3 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | II | ..... | 17 900 | ..... | ..... | 3 | 4 | ..... | 12 | 50 |
| 4 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | ..... | ..... | 16 900 | ..... | ..... | 2 | 5.5 | ..... | 13 | 54 |
| G2-1 | 3.0 | ..... | .9 | ..... | ..... | 775 | 700 | III | ..... | 20 500 | ..... | ..... | 4 | 10 | ..... | 14 | 54 |
| 2 | ..... | ..... | ..... | ..... | ..... | 775 | 700 | II | ..... | 19 200 | ..... | ..... | 2 | 6.5 | ..... | 13 | 55 |
| 3 | ..... | ..... | ..... | ..... | ..... | 775 | 700 | III | ..... | 21 100 | ..... | ..... | 5 | 5 | ..... | 12 | 53 |
| 4 | ..... | ..... | ..... | ..... | ..... | 775 | 700 | II | ..... | 19 000 | ..... | ..... | 3 | 4.5 | ..... | ..... | 50 |
| G1-C | (2) | ..... | (1) | ..... | ..... | 800 | 700 | III | ..... | 18 700 | 3500 | ..... | 5 | 2.5 | ..... | ..... | 48 |
| D | ..... | ..... | ..... | ..... | ..... | 800 | 700 | III | ..... | 19 900 | 3500 | ..... | 5 | 4 | ..... | 10 | 45 |
| H | ..... | ..... | ..... | ..... | ..... | 800 | 700 | III | ..... | 19 400 | 1500 | ..... | 5 | 4.5 | ..... | 10 | 45 |
| I | ..... | ..... | ..... | ..... | ..... | 800 | 700 | III | ..... | 18 600 | 1750 | ..... | 6 | 3.5 | ..... | 10 | 46 |
| K | ..... | ..... | ..... | ..... | ..... | 800 | 700 | III | ..... | 19 700 | 2250 | ..... | 6 | 5 | ..... | 11 | 46 |
| L | ..... | ..... | ..... | ..... | ..... | 800 | 700 | III | ..... | 18 900 | 2400 | ..... | 5 | 3.5 | ..... | 10 | 44 |
| M | ..... | ..... | ..... | ..... | ..... | 850 | 850 | III | ..... | 12 100 | 4250 | ..... | 3 | 2 | ..... | ..... | 44 |
| N | ..... | ..... | ..... | ..... | ..... | 850 | 850 | III | ..... | 13 100 | 5000 | ..... | 3 | 1.5 | ..... | 10 | 42 |
| O | ..... | ..... | ..... | ..... | ..... | 850 | 850 | III | ..... | 18 500 | 4500 | ..... | 6 | 3.5 | ..... | 11 | 50 |
| P | ..... | ..... | ..... | ..... | ..... | 850 | 850 | III | ..... | 19 300 | 2500 | ..... | 7 | 3 | ..... | 12 | 50 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G1-R | (2) | | (1) | | | | 700 | IV | ac | 29 500 | | 12 000 | 1.5 | .8 | | 24 | 76 |
| S | | | | | | | 700 | IV | | 17 250 | | 10 500 | .8 | 1.0 | | 22 | 65 |
| G1-A | (2) | | (1) | | | | 700 | V | | | | | | | | | |
| B | | | | | | | 700 | V | | 22 900 | | 10 000 | 1.6 | 2.0 | | 18 | 63 |
| G | | | | | | | | IV | ac | 24 900 | | | .8 | 2.0 | | 20 | 73 |
| 3 | | | | | | | | IV | ac | 24 500 | | 9000 | 2.3 | 4.0 | | 20 | 70 |
| 2 | 2.9 | 0.4 | .4 | | | | | IV | | 17 900 | | 11 500 | 0 | 1.0 | | 20 | 62 |
| 4 | | | | | | | | IV | | 19 700 | | 7500 | 0 | 0 | | 18 | 53 |
| G3-12 | (2) | | (1) | | | | 700 | III | | 23 400 | | | 3 | 2.0 | | 12 | 60 |
| 13 | | | | | | | 700 | III | ac | 29 900 | | | 2.5 | 2.8 | | 15 | 74 |
| G4-B | 3.4 | | .6 | | .5 Fe | 775 | 700 | III | | 19 500 | 4600 | | 3 | 2.3 | | 10 | 50 |
| C | | | | | .4 Si | 775 | 700 | III | | 17 500 | | | 3 | 1.6 | | 10 | 52 |
| A | | | | | | 775 | 700 | III | ac | 25 400 | | | 7.5 | 4.7 | | 11 | 57 |
| D | | | | | | 775 | 700 | III | ac | 21 100 | | | 3 | 1.6 | | 10 | 68 |
| G5-B | 4.9 | | .9 | | | 800 | 700 | III | | 19 200 | | | 1 | .4 | | 12 | 66 |
| C | | | | | | 800 | 700 | III | | 15 700 | | | 3 | 1.6 | | 12 | 55 |
| A | | | | | | 800 | 700 | III | ac | 12 700 | | | 1.5 | 0 | | 12 | 64 |
| D | | | | | | 800 | 700 | III | ac | 15 900 | | | 0 | 0 | | 13 | 60 |
| G7-E | 1.8 | | 1.2 | | | | 700 | V | | 21 400 | | 5000 | 7.5 | 9.9 | | 12 | 44 |
| H | | | | | | | 700 | V | | 21 200 | | 4000 | 6.5 | 7.9 | | 11 | 43 |
| F | | | | | | | 700 | V | ac | 24 100 | | 5000 | 6.5 | 8.0 | | 12 | 50 |
| G | | | | | | | 700 | V | ac | 22 300 | | 4000 | 5.5 | 8.0 | | 12 | 45 |
| G8-B | 1.8 | 1.7 | 1.2 | | | | 700 | V | | 24 000 | | 12 500 | .5 | 2.0 | | 12 | 70 |
| D | | | | | | | 700 | V | | 24 900 | | 11 000 | 1.5 | .9 | | 11 | 74 |
| A | | | | | | | 700 | V | ac | 30 700 | | 13 500 | 1.0 | 1.0 | | 10 | 74 |
| C | | | | | | | 700 | V | ac | 31 500 | | 13 000 | 2.0 | 2.0 | | 14 | 70 |
| G9-E | 3.7 | | 8 | | | | 700 | V | | 23 500 | | 4000 | 7.5 | | | 12 | 45 |
| F | | | | | | | 700 | V | ac | 25 700 | | 4000 | 7.0 | | | 10 | 48 |
| G10-E | (1.5) | | (1.5) | | | 850 | 700 | V | | 22 800 | | 4000 | 13.5 | 13.5 | | | |
| F | | | | | | 850 | 700 | V | ac | 25 100 | | 4000 | 7.5 | 8.5 | | | |
| G11-E | (1.5) | | (1.5) | | | 800 | 700 | V | ac | | | | | | | | |
| F | | | | | | 800 | 700 | V | | 25 500 | | 4000 | 8.0 | 7.5 | | | |
| G12-E | (1.5) | | (1.5) | | | 920 | 700 | | | 20 000 | | 4100 | 7.0 | 11.8 | | | |
| F | | | | | | 920 | 700 | | | 16 150 | | | 2.0 | | Blowhole | | |

## TABLE 1—Continued

(*d*) CAST ALLOYS CONTAINING COPPER, MANGANESE, AND NICKEL

| Heat and No. | Chemical composition | | | | | Temperature | | Form of test bar | Heat treatment | Tensile properties | | | | | | Hardness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Copper | Magnesium | Manganese | Nickel | Other metals | Maximum temperature during pouring | Pouring temperature | | | Ultimate strength | Yield point | Proportional limit | Elongation in 2 inches | Reduction of area | Fracture | Scleroscope mag. hammer | Brinell, 500 kg |
| | P. ct. | P. ct. | P. ct. | P. ct. | Per cent | °C | °C | | | Lbs./in.² | Lbs./in.² | Lbs./in.² | Per cent | Per cent | | | |
| H1-1 | (3) | ..... | (0.75) | (*a*) | ..... | ..... | 700 | III | ..... | 21 400 | ..... | ..... | 4 | 4.5 | ..... | 15 | 50 |
| 2 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 21 700 | ..... | ..... | 6 | 4 | ..... | 14 | 54 |
| 3 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | II | ..... | 21 300 | ..... | ..... | 6 | 4 | ..... | 14 | 54 |
| 4 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | II | ..... | 21 500 | ..... | ..... | 5 | 5 | ..... | 14 | 56 |
| H2-1 | (3) | ..... | (.75) | (*a*) | 1 Ha (*b*) | ..... | 700 | III | ..... | 25 500 | ..... | ..... | 6 | 10 | ..... | 15 | 61 |
| 2 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 25 200 | ..... | ..... | 4 | 11 | ..... | 15 | 62 |
| 3 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | II | ..... | 20 600 | ..... | ..... | 4 | 4 | ..... | 16 | 61 |
| 4 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | II | ..... | 25 100 | ..... | ..... | 4 | 10.5 | ..... | 14 | 64 |
| H4-1 | 40 | 1.0 | .2 | 1.0 | ..... | ..... | 700 | IV | ac | 30 500 | ..... | 13 000 | .8 | 1 | ..... | 27 | 91 |
| 2 | ..... | ..... | ..... | ..... | ..... | ..... | 700 | IV | ..... | 25 500 | ..... | 13 000 | 0 | 1 | ..... | 25 | 80 |
| H1-A | 3.7 | .6 | .3 | 1.0 | ..... | ..... | 700 | IV | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| B | ..... | ..... | ..... | ..... | ..... | ..... | 700 | ..... | ..... | 25 500 | ..... | 12 500 | 0 | .5 | ..... | ..... | ..... |
| H5-E | 3.1 | ..... | .8 | 1.5 | ..... | ..... | 700 | V | ..... | 24 400 | ..... | 7000 | 4 | 8.4 | ..... | 10 | 54 |
| H | ..... | ..... | ..... | ..... | ..... | ..... | 700 | V | ..... | 25 400 | ..... | 6000 | 6 | 8.5 | ..... | 10 | 54 |
| F | ..... | ..... | ..... | ..... | ..... | ..... | 700 | V | ac | 27 000 | ..... | 5000 | 3.5 | 5.0 | ..... | 9 | 57 |
| G | ..... | ..... | ..... | ..... | ..... | ..... | 700 | V | ac | 24 800 | ..... | 5000 | 4.5 | 4.5 | ..... | 9 | 61 |
| H6-B | 3.1 | .9 | .8 | 1.5 | ..... | ..... | 700 | V | ..... | 33 000 | ..... | 14 000 | 1.5 | 1.5 | ..... | 17 | 86 |
| D | ..... | ..... | ..... | ..... | ..... | ..... | 700 | V | ..... | 27 100 | ..... | 12 000 | ..... | ..... | ..... | 19 | 86 |
| A | ..... | ..... | ..... | ..... | ..... | ..... | 700 | V | ac | 29 700 | ..... | 13 000 | 1.0 | 1.9 | ..... | 17 | 86 |
| C | ..... | ..... | ..... | ..... | ..... | ..... | 700 | V | ac | 35 600 | ..... | 16 000 | 2.0 | 1.9 | ..... | 18 | 86 |
| H | (3) | ..... | (.75) | (*a*) | ..... | ..... | ..... | ..... | ..... | 27 000 | ..... | 12 500 | .8 | 1.5 | ..... | ..... | ..... |

### (e) CAST ALLOYS CONTAINING COPPER AND MAGNESIUM

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E23-A | (1.5) | | | | | 900 | 700 | III | | 18 000 | | 2800 | 8.5 | 11.5 | | | |
| B | | | | | | 900 | 700 | III | | 17 000 | | 3400 | 5.5 | 6.5 | | | |
| AA | | | | | | 900 | 700 | VI | | 20 000 | | 2500 | 12.5 | 16.5 | | | |
| BB | | | | | | 900 | 700 | VI | | 19 500 | | 1800 | 11.5 | 13.0 | | | |
| X | | | | | | 900 | 700 | VII | | 16 200 | | 3900 | 4 | 8 | | | |
| Y | | | | | | 900 | 700 | VII | | 19 200 | | 3500 | 10.5 | 12 | | | |
| E24-A | (2.5) | | | | | 800 | 700 | III | | | | | | | | | |
| B | | | | | | 800 | 700 | III | ac | 17 400 | | 3000 | 6 | 10.5 | | | |
| AA | | | | | | 800 | 700 | VI | | 19 900 | | 2500 | 8 | 13.0 | | | |
| BB | | | | | | 800 | 700 | VI | | 17 900 | | 4000 | 4 | 7.0 | | | |
| C | | | | | | 800 | 700 | VI | | | | | | | | | |
| D | | | | | | 800 | 700 | VI | ac | 21 300 | | 3200 | 6.5 | 10.5 | | | |
| (A) X | | | | | | 800 | 700 | VII | | 19 400 | | 2800 | 4.5 | 3.9 | | | |
| (B) Y | | | | | | 800 | 700 | VII | | 18 100 | | 2000 | 5.5 | 10 | | | |
| E26-B | (3.5) | | | | | 900 | 900 | VI | | 17 800 | | 5800 | 4.5 | 7.0 | | | |
| BB | | | | | | 900 | 900 | VI | | 17 300 | | 3800 | 3.5 | 5.0 | | | |
| C | | | | | | 900 | 700 | VI | | 22 300 | | 3800 | 8.0 | 12.0 | | | |
| CC | | | | | | 900 | 700 | VI | | | | | | | | | |
| E27-A | (3.5) | | | | | 775 | 700 | VI | | 17 700 | | 3000 | 7.0 | 10.5 | | | |
| B | | | | | | 775 | 700 | VI | | 18 400 | | 3000 | 5.5 | 7.0 | | | |
| C | | | | | | 775 | 700 | VI | ac | 21 600 | | 3300 | 11.0 | 9.0 | | | |
| D | | | | | | 775 | 700 | VI | ac | 21 700 | | 2900 | 8.5 | 10.0 | | | |
| E | | | | | | 775 | 700 | VII | | 18 700 | | 4000 | 7.0 | 12.5 | | | |
| F | | | | | | 775 | 700 | VII | | 18 700 | | 3000 | 8.0 | 7.0 | | | |
| E27-G | | | | | | 775 | 700 | III | | 15 600 | | 4000 | 4.5 | 6.0 | | | |
| H | | | | | | 775 | 700 | III | | 14 900 | | 2800 | 5.0 | 6.0 | | | |
| J | | | | | | 950 | 950 | VI | | 14 300 | | 3800 | 6.0 | 3.5 | | | |

[a] ac means that the specimen was annealed 2 hours at 500° C and cooled in air.

[b] Ha is a hardener, supplied by Maj. G. L. Norris, of the following composition:

| | Per cent |
|---|---|
| Vanadium | 12.63 |
| Manganese | 26.69 |
| Aluminum | 55.93 |
| Iron | 1.20 |
| Silicon | 3.70 |

## TABLE 1—Continued

(e) CAST ALLOYS CONTAINING COPPER AND MAGNESIUM—Continued

| Heat and No. | Chemical composition | | | | | Temperature | | Form of test bar | Heat treatment | Tensile properties | | | | | | Hardness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Copper | Magnesium | Manganese | Nickel | Other metals | Maximum temperature during pouring | Pouring temperature | | | Ultimate strength | Yield point | Proportional limit | Elongation in 2 inches | Reduction of area | Fracture | Scleroscope mag. hammer | Brinell, 500 kg |
| | P. ct. | P. ct. | P. ct. | P. ct. | Per cent | °C | °C | | | Lbs./in.² | Lbs./in.² | Lbs./in.² | Per cent | Per cent | | | |
| E27-K | | | | | | 950 | 950 | VI | | 12 900 | | 3000 | 5.5 | 7.0 | | | |
| L | | | | | | 950 | 700 | VI | | 16 600 | | 3300 | 5.0 | 8.5 | | | |
| M | | | | | | 950 | 700 | VI | | 14 900 | | 4000 | 3.5 | 5.5 | Large blowhole. | | |
| C15-B | 3.1 | 1.3 | | | 0.4 Fe | | 700 | III | ac | 18 500 | 7500 | | 3 | 0 | | 22 | 82 |
| D | | | | | .3 Si | | 700 | III | tc[a] | 18 200 | 8500 | | 3 | 1 | | 17 | 69 |
| C | | | | | | | 700 | III | | 15 000 | 5000 | | 1 | 0 | | 21 | 79 |
| E | | | | | | | 700 | III | | 15 700 | 4000 | | 2 | 0 | | 19 | 76 |
| C16-B | 3.4 | .4 | | | | | 700 | III | ac | 17 200 | 4500 | | 2 | 1 | | 18 | 72 |
| D | | | | | | | 700 | III | tc | 18 600 | 3000 | | 4 | 1.5 | | 16 | 68 |
| C | | | | | | | 700 | III | | 10 900 | 3500 | | 2 | .5 | | 17 | 69 |
| E | | | | | | | 700 | III | | 16 400 | 7000 | | 1 | .5 | | 16 | 64 |
| C17-B | 3.1 | 1.1 | | | | | 700 | III | ac | 18 500 | | | 2 | 0 | | 25 | 89 |
| D | | | | | | | 700 | III | tc | 13 200 | 5500 | | 2 | 0 | | 22 | 77 |
| C | | | | | | | 700 | III | | | | | | | | | |
| E | | | | | | | 700 | III | | 19 300 | 8500 | | 5 | 1 | | 23 | 82 |
| CA-40-E | (3) | (1) | | | | | 700 | III | | 21 000 | | | 1 | 0 | | 22 | 80 |
| F | | | | | | | 700 | III | | 10 400 | 5000 | | 3 | 0 | | 22 | 79 |
| C18-B | A2 | .6 | | | | | | III | ac | 24 900 | 6500 | | 3 | 1 | | 21 | 80 |
| D | | | | | | | | III | tc | 18 600 | 6000 | | 2 | 0 | | 15 | 69 |
| C | | | | | | | | III | | 13 600 | 4500 | | | 0 | | 17 | 74 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E | | | | | | | | III | | 18 900 | 6500 | | 2 | 0.5 | | 18 | 74 |
| C19–B | 2.5 | 1.0 | 0.4 | | | | 700 | III | ac | 31 400 | | | 4 | 2 | | 23 | 86 |
| D | | | | | | | 700 | III | fc | 27 900 | 5500 | | 3 | 2.5 | | 18 | 69 |
| C | | | | | | | 700 | III | | 19 300 | 4000 | | 2 | 0 | | 21 | 74 |
| E | | | | | | | 700 | III | | 17 000 | 5500 | | 2 | 0 | | 20 | 74 |
| C44–A | 6.0 | 2.2 | | | | .4 Fe | 700 | III | ac | 12 600 | | | 1.5 | 0 | | 42 | 129 |
| D | | | | | | .5 Si | 700 | III | ac | 14 300 | | | 1 | 0 | | 38 | 133 |
| B | | | | | | | 700 | III | | 15 400 | | | 2 | 0 | | 27 | 96 |
| C | | | | | | | 700 | III | | 15 900 | | | 2 | .5 | | 26 | 92 |
| C45–A | 3.9 | 2.0 | .6 | | | | 700 | III | ac | 18 000 | | | 1 | .5 | | 30 | 98 |
| D | | | | | | | 700 | III | ac | 11 700 | | | 1.5 | 0 | | 29 | 92 |
| B | | | | | | | 700 | III | | 10 700 | | | 1 | 0 | | 25 | 84 |
| C | | | | | | | 700 | III | | 10 500 | | | 1.5 | 0 | | 24 | 80 |
| C47–A | 3.9 | .9 | .4 | | | | 875 | 700 | III | ac | 16 500 | | | 1 | .5 | | 25 | 75 |
| G | | | | | | | 875 | 700 | III | ac | 15 700 | | | 1 | .5 | | 25 | 92 |
| B | | | | | | | 875 | 700 | III | | 14 100 | | | 1.5 | .5 | | 22 | 74 |
| F | | | | | | | 875 | 700 | III | | 13 200 | | | 1 | 0 | | 20 | 68 |
| C56–A | 2.5 | 1.2 | | | | | 700 | 700 | V | ac | 26 900 | | | 1.6 | 1.0 | | 26 | 81 |
| C | | | | | | | 700 | 700 | V | ac | 28 100 | | 14 000 | .8 | 1.2 | | 27 | 82 |
| B | | | | | | | 700 | 700 | V | | 22 700 | 5600 | | 1.6 | 1.5 | | 20 | 65 |
| D | | | | | | | 700 | 700 | V | | 21 700 | | 9800 | 1.5 | 1.6 | | 20 | 60 |
| C57–A | 2.5 | .8 | | 1.9 | | | 750 | 700 | V | ac | 31 800 | | 8000 | .8 | 1 | | 22 | 80 |
| C | | | | | | | 750 | 700 | V | ac | 32 300 | | 6000 | .8 | 1.5 | | 25 | 81 |
| B | | | | | | | 750 | 700 | V | | 26 900 | | 4000 | 1.6 | 1.5 | | 21 | 75 |
| D | | | | | | | 750 | 700 | V | | 26 300 | | 12 500 | | 1.0 | | 25 | 68 |
| C20–A | 2.3 | 1.3 | 1.4 | | | .4 Fe | 800 | 700 | V | ac | 35 000 | | 12 300 | 2.3 | 3.5 | | 28 | 86 |
| C | | | | | | .3 Si | 800 | 700 | V | ac | 35 500 | | 15 200 | 2.3 | 2.5 | | 27 | 85 |
| B | | | | | | | 800 | 700 | V | | 25 900 | | 12 000 | 1.6 | 1.0 | | 25 | 75 |
| D | | | | | | | 800 | 700 | V | | 23 600 | | 12 000 | 1.6 | 2.5 | | 21 | 75 |
| J1–1 | (1) | (1) | | (1) | | | 800 | 700 | III | | 24 800 | | | 1.5 | 1.5 | | | |
| 2 | | | | | | | 800 | 700 | III | | 25 000 | | | 1 | 1.2 | | | |
| 3 | | | | | | | 800 | 700 | III | | 25 300 | | | 1 | .8 | | | |
| 4 | | | | | | | 800 | 700 | III | | 22 300 | | | 1 | 1.2 | | | |

[a] fc indicates that after the same annealing the specimen was cooled in the furnace.

## TABLE 1—Continued

(c) CAST ALLOYS CONTAINING COPPER AND MAGNESIUM—Continued

| Heat and No. | Chemical composition | | | | | Temperature | | Form of test bar | Heat treatment | Tensile properties | | | | | | Hardness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Copper | Magnesium | Manganese | Nickel | Other metals | Maximum temperature during pouring | Pouring temperature | | | Ultimate strength | Yield point | Proportional limit | Elongation in 2 inches | Reduction of area | Fracture | Scleroscope mag. hammer | Brinell, 500 kg |
| | P. ct. | P. ct. | P. ct. | P. ct. | Per cent | °C | °C | | | Lbs./in.² | Lbs./in.² | Lbs./in.² | Per cent | Per cent | | | |
| J1-E | 1.0 | 0.7 | 0.8 | ..... | ..... | 850 | 700 | V | ..... | 23 700 | 7700 | ..... | 4.6 | 4.1 | ..... | 14 | 54 |
| H | ..... | ..... | ..... | ..... | ..... | 850 | 700 | V | ..... | 23 800 | ..... | 6000 | 4.7 | 3.1 | ..... | 14 | 54 |
| F | ..... | ..... | ..... | ..... | ..... | 850 | 700 | V | ac | 26 500 | 5300 | ..... | 4.6 | 3.7 | ..... | 20 | 63 |
| G | ..... | ..... | ..... | ..... | ..... | 850 | 700 | V | ac | 26 600 | ..... | 9800 | 3.1 | 2.1 | ..... | 20 | 61 |
| J2-A | 1.6 | .4 | ..... | 1.4 | ..... | 825 | 700 | V | ..... | 25 300 | 6200 | ..... | 4.6 | 2.1 | ..... | 17 | 55 |
| D | ..... | ..... | ..... | ..... | ..... | 825 | 700 | V | ..... | 25 600 | ..... | 11 000 | 1.6 | 2.8 | ..... | 19 | 61 |
| B | ..... | ..... | ..... | ..... | ..... | 825 | 700 | V | ac | 26 400 | ..... | ..... | 3.1 | 2.0 | ..... | 19 | 63 |
| C | ..... | ..... | ..... | ..... | ..... | 825 | 700 | V | ac | 25 100 | ..... | 5300 | 2.3 | 2.1 | ..... | 20 | 71 |
| C49-A | 3.3 | .8 | ..... | ..... | 3.6 SN | 725 | 700 | V | ac | 19 900 | ..... | ..... | 0 | .5 | ..... | 23 | 72 |
| C | ..... | ..... | ..... | ..... | ..... | 725 | 700 | V | ac | 18 300 | ..... | 14 000 | .8 | 1.5 | ..... | 26 | 74 |
| B | ..... | ..... | ..... | ..... | ..... | 725 | 700 | V | ..... | 18 600 | ..... | ..... | 1.6 | 1.1 | ..... | 22 | 63 |
| D | ..... | ..... | ..... | ..... | ..... | 725 | 700 | V | ..... | 16 000 | ..... | 13 000 | .8 | 3.2 | ..... | 19 | 65 |
| C53-A | 3.4 | 1.5 | ..... | ..... | .4 Fe | 750 | 700 | V | ac | 25 000 | ..... | 10 500 | 0 | 0 | ..... | 24 | 85 |
| C | ..... | ..... | ..... | ..... | .3 Si | 750 | 700 | V | ac | 15 100 | ..... | 10 000 | 1.6 | .6 | ..... | 27 | 84 |
| B | ..... | ..... | ..... | ..... | 4.5 Fn | 750 | 700 | V | ac | 20 500 | ..... | 14 000 | .8 | .5 | ..... | 25 | 84 |
| D | ..... | ..... | ..... | ..... | ..... | 750 | 700 | V | ..... | 22 700 | ..... | 12 500 | .8 | .5 | ..... | 26 | 85 |
| C59-A | 2.7 | .9 | ..... | .2 | 2.8 Cd | 750 | 700 | V | ac | 29 500 | ..... | 12 500 | .8 | 0 | ..... | 25 | 78 |
| C | ..... | ..... | ..... | ..... | ..... | 750 | 700 | V | ac | 30 300 | ..... | 10 800 | 1.6 | 1.0 | ..... | 25 | 81 |
| B | ..... | ..... | ..... | ..... | ..... | 750 | 700 | V | ..... | 24 100 | ..... | 8500 | 1.6 | 2.1 | ..... | 17 | 62 |
| D | ..... | ..... | ..... | ..... | ..... | 750 | 700 | V | ..... | 25 400 | ..... | 13 000 | 2.3 | 2.5 | ..... | 19 | 64 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G6-A | 2.1 | 1.1 | 1.1 | ..... | ..... | 700 | 700 | III | ac | 25 700 | ..... | ..... | .5 | .4 | ..... | 23 | 87 |
| G | ..... | ..... | ..... | ..... | ..... | 700 | 700 | III | ac | 28 000 | 4100 | ..... | 2.5 | 1.2 | ..... | 22 | 89 |
| B | ..... | ..... | ..... | ..... | ..... | 700 | 700 | III | ..... | 15 600 | ..... | ..... | 1 | 0 | ..... | 17 | 74 |
| F | ..... | ..... | ..... | ..... | ..... | 700 | 700 | III | ..... | 19 600 | ..... | ..... | 1 | .4 | ..... | 17 | 74 |
| H3-1 | 3.4 | 1.3 | ..... | 1.7 | .5 Fe | 775 | 700 | IV | ac | 26 600 | ..... | ..... | 1.6 | 1.0 | ..... | 25 | 84 |
| 4 | ..... | ..... | ..... | ..... | .5 Si | 775 | 700 | IV | ac | 26 300 | ..... | 10 500 | 0 | .5 | ..... | 27 | 85 |
| 2 | ..... | ..... | ..... | ..... | ..... | 775 | 700 | IV | ..... | 24 500 | ..... | 10 000 | .8 | .5 | ..... | 24 | 80 |
| 3 | ..... | ..... | ..... | ..... | ..... | 775 | 700 | IV | ..... | 24 300 | ..... | 9500 | .8 | .5 | ..... | 26 | 80 |

### (*f*) CAST COPPER-ZINC AND MAGNESIUM ALLOYS

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A30-C | ..... | (5) | ..... | ..... | ..... | ..... | 700 | III | ..... | 19 300 | 4000 | ..... | 2 | ..... | ..... | 17 | 64 |
| D | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 20 700 | 4000 | ..... | 4 | ..... | ..... | 14 | 65 |
| Z-1 | 2.3 | .5 | ..... | ..... | 4.1 Zn | ..... | ..... | IV | ..... | 25 500 | ..... | ..... | 1.5 | ..... | ..... | 19 | 65 |
| Z14-E | 2.9 | ..... | ..... | ..... | 12.7 Zn | 750 | 700 | ..... | ac | 37 300 | ..... | 6900 | 5.5 | 9.9 | ..... | ..... | ..... |
| F | ..... | ..... | ..... | ..... | ..... | 750 | 700 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| Z15-E | 3.0 | ..... | ..... | ..... | 8.4 Zn | 750 | 700 | VI | ..... | 26 600 | ..... | 7500 | 5.5 | 6.0 | ..... | 12 | 54 |
| H | ..... | ..... | ..... | ..... | ..... | 750 | 700 | VI | ..... | 26 000 | ..... | 6000 | 5.0 | 6.9 | ..... | 12 | 52 |
| F | ..... | ..... | ..... | ..... | ..... | 750 | 700 | VI | ac | 28 600 | ..... | 5000 | 8.0 | 7.5 | ..... | 10 | 50 |
| G | ..... | ..... | ..... | ..... | ..... | 750 | 700 | VI | ac | 29 100 | ..... | 7500 | 8.0 | 7.5 | ..... | 10 | 50 |
| Z16-E | 3.0 | ..... | ..... | ..... | 15.9 Zn | ..... | ..... | V | ..... | 35 100 | ..... | 14 000 | 2.0 | 2.0 | ..... | 15 | 74 |
| F | ..... | ..... | ..... | ..... | ..... | ..... | ..... | V | ac | 41 200 | ..... | 14 000 | 4.0 | 4.0 | ..... | 15 | 70 |
| Z31-C | 3.2 | ..... | ..... | ..... | 13.7 Zn | ..... | 700 | III | ..... | 22 800 | 3250 | ..... | 3 | ..... | ..... | 20 | 68 |
| D | ..... | ..... | ..... | ..... | ..... | ..... | 700 | III | ..... | 23 000 | 3400 | ..... | 2 | ..... | ..... | 20 | 71 |

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